Proceedings – 23rd Annual Conference – IEEE/EMBS Oct.25-28, 2001, Istanbul, TURKEY

TARGET PROBABILITY MODULATES NEURONAL ACTIVITY IN THE PRIMATE SACCADIC SYSTEM

M. A. Basso
Department of Physiology, University of Wisconsin – Madison, WI, USA

Abstract-**The brain has a limited capacity to process information, so perceptual discriminations made when viewing natural visual scenes require that individual stimuli be singled out as targets for further analysis. Motor systems are similarly challenged since goal directed behaviors - by definition - require identification of a single goal. The current report focuses on whether neuronal activity within structures related to the generation of rapid reorienting movements of the eyes, saccades, show modulations related to the probability of selecting one target from among many. We recorded from neurons in the Superior Colliculus (SC) and the Substantia Nigra Pars Reticulata (SNr) while monkeys performed a task in which the number of possible targets was manipulated. We found that neurons in both regions were modulated with changes in target probability. When the probability of a particular saccade target was high, the activity of SC neurons was also high. When the probability was low, the activity was low. Neuronal activity in the SNr was also modulated in a manner similar but not identical to that seen in SC. The results suggest that neuronal elements in these regions reflect task demands similar to that seen in cortical regions involved in visual perception.**

***Keywords* – Target Selection, Superior Colliculus, Substantia Nigra, Inhibition**

I. INTRODUCTION

The superior colliculi (SC) are located on the roof of the midbrain and receive direct inputs from the retina as well as virtually the entirety of cerebral cortex. The SC, in turn, directly access brainstem regions critical for the production of rapid reorienting movements of the eyes - saccades. Much research has been devoted to demonstrating that neuronal elements within the SC are intimately involved in the production of saccadic eye movements [1].

In addition to the direct inputs from cortex, the SC receive indirect cortical inputs through the basal ganglia. In particular, the substania nigra pars reticulata (SNr) has direct projections to the saccade-related regions of the SC [2, 3]. In contrast to the direct excitatory cortical inputs, those from the SNr provide a major source of inhibition to the SC [4]. This cortical convergence in both the SC and the SNr make these two regions ideal for assessing the output and processing of these two descending pathways, the direct cortico-brainstem pathway and the indirect cortico-basal ganglia-brainstem pathway. Indeed, both structures, the SC and the SNr contain neuronal elements with response properties reflecting visual stimuli as well as saccadic eye movements. Far less is known about the role, if any, these structures play in events intervening between visual stimulus presentation and saccadic eye movement generation. Therefore, the goal of the work described here was to measure the neuronal activity in these two saccade-related regions, the SC and the SNr, in a behavioral task in which events preceding saccadic eye movements were manipulated. In particular, we presented monkeys with many possible stimuli from which only one would later be identified as a target for a saccadic eye movement. We manipulated the number of possible visual targets available for selection while we recorded neurons in the SC and the SNr. This was done to determine whether the activity of these neurons is linked only to the generation of the saccadic eye movement or whether it reflects processes occurring between vision and action such as saccade target selection.

0-7803-7211-5/01$10.00@2001 IEEE

II. METHODOLOGY

Two monkeys were prepared for recording single neurons in the SC and two were prepared for the SNr using standard techniques [for details see 5, 6]. All procedures complied with the Public Health Service Policy on the humane care and use of laboratory animals and were approved by the Institute Animal Care and Use Committee. In our target probability task (Fig. 1), our goal was to separate the sequence of events leading up to saccade generation while varying the probability that a given stimulus would become a saccade target.

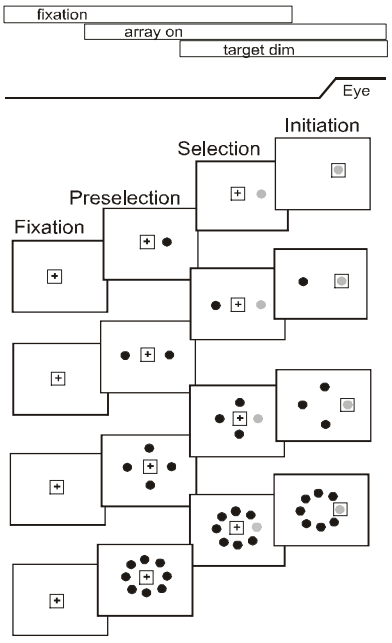

Fig. 1. Target probability task. The upper portion represents the temporal arrangement of the task and the lower portion represents the spatial arrangement of the task. The boxes represent the video screen viewed by the monkeys. The smaller inset boxes represent the eye position requirement of the task. Note that the trace marked “Eye” is schematic.

First, a centrally located fixation point (LED) was illuminated and monkeys were required to look at it for 1 s to initiate the trial. Second, one, two, four, or eight spots of light were illuminated for a randomized time ranging from 800 - 1200

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle Target Probability Modulates Neuronal Activity in The Primate Saccadic System	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Department of Physiology University of Wisconsin Madison, WI	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.

Abstract

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU

Number of Pages
4

ms, and these trial types were randomly interleaved. This was the period of pre-selection because which of the spots would become the target was unknown to the monkeys. Because neurons in the SC and SNr show preferences for the location of targets or saccades, one of the spots was always located at the position in the visual field that yielded the maximal response from the recorded neuron. SNr neurons generally show a decline in activity associated with saccades [7-9] so for these neurons, we sought a maximal pause in activity. All other possible targets were placed equally eccentric but in different directions. Third, one of the possible targets dimmed for 800 - 1200 ms. We defined this as the period of selection because the dimming indicated which of the spots was the target for the saccade. The final period of saccade initiation began when the fixation point went off (go signal) which required monkeys to make a saccade within 500 ms to the dimmed target. Monkeys were required to maintain their eye position at the target for 300 - 500 ms in order to obtain liquid reward.

III. RESULTS

A. Superior Colliculus Neurons

Recordings from neurons in the SC while monkeys perform saccades to flashed spots of light reveal some neurons with activity tightly linked to the onset of visual stimuli and some neurons with activity tightly linked to the initiation of saccades. Other neurons contain activity tightly linked to both visual stimuli and saccade initiation. Having monkeys perform tasks in which time is imposed between the stimulus presentation and the cue to initiate a movement (delayed response task) reveals SC neuronal activity during the delay period as well (Fig. 2).

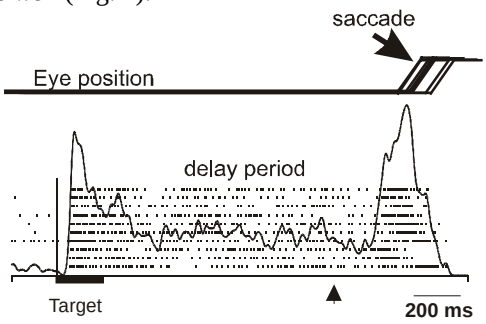

Fig. 2. Neuronal activity recorded from the SC during performance of a delayed saccade task. Each tick is a single action potential and each row of ticks is an individual trial. The envelope of activity is the spike density function describing the average activity across the trials. The bar indicates the onset and duration of the visual stimulus and the arrow indicates the time the fixation point was removed.

Whereas it is generally considered that the discharge of action potentials associated with the onset of a saccade reflects a command to initiate an eye movement and the initial visual activity reflects a potential eye movement [10, 11] it is less clear what the activity of these neurons during the delay period represents. One possibility is that it is reflective of processes intervening between vision and action, processes that are occurring during the delay period such as target selection and saccade preparation [12, 13]. Therefore, our task was designed to present a more complicated visual scene thereby manipulating the probability that monkeys would engage in processes preceding saccade initiation.

When a single possible target was presented, buildup neurons of the SC exhibited activity associated with the onset of the visual stimulus and maintained activity during the preselection period before the target was identified (Fig. 3, first row). At the time the target was identified by dimming, there was not much change in the neuronal activity with a single possible target. Later, after the go signal occurred, there was an additional discharge of action potentials associated with the onset of the saccadic eye movement. When the number of possible targets was increased thus decreasing the probability of selecting a particular saccade target, the activity of SC neurons was reduced. The initial visual response was reduced as well the longer latency delay period activity (Fig. 3, left and middle columns).

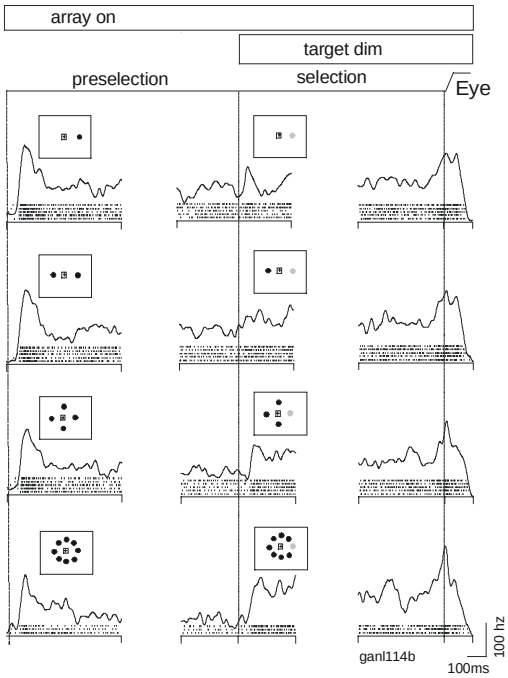

Fig. 3. SC neuron and changes in target probability. The boxes represent the video screen viewed by the monkeys and the gray circle indicates the identified target. Each tick is an action potential and each row of ticks is an individual trial. The spike density function is superimposed. Data are taken from correct trials only. The trace marked “Eye” is schematic.

Indeed, the activity was most reduced when the probability of selecting a particular target was most reduced, with eight possible saccade targets. At the time the target was identified, in the eight possible target condition, there was an increase in the activity of these neurons that was most noticeable. During this interval, the neuronal activity remained at levels seen in the single target condition independent of the number of visual stimuli on the screen until the time the saccade was initiated. At this point, there was the discharge of action potentials associated with saccade initiation. The saccade discharge was similar in the different conditions because the saccade was directed to the same location in each case. We saw significant modulations with changes in target probability for all SC neurons we recorded [see 5].

In summary, neuronal activity in the SC reflects the probability that a particular saccade target will be identified for a saccade. When the target probability is high, neuronal activity is high. When target probability is low, neuronal activity is low. When one stimulus is identified as a target, the

activity increases reflecting the increased probability of selecting the target. Therefore, despite their proximity to the final common pathway for saccades, activity of these neuronal elements within the SC reflects processes preceding the generation of a saccade and is not obligately linked to the generation of a saccade.

B. Substantia Nigra Neurons

SC neurons receive inputs from many sources. In general these inputs are considered excitatory. One set of inputs arising from an output nucleus of the basal ganglia is the substantia nigra pars reticulata (SNr). The action of the SNr is to inhibit its target structures [4]. Consistent with this, neurons in the SNr are tonically active and cease to discharge action potentials at the time of saccade initiation as well as with the onset of visual stimuli [7, 8]. The activity profile of SNr neurons at the time of saccade initiation is essentially a mirror-image of the activity profiles recorded in saccade related neurons of the SC [3, but see also 9]. Therefore, one hypothesis is that the pause in discharge of SNr neurons disinhibits the SC allowing the initiation of a saccadic eye movement [3, 14]. Whether or not these neurons are involved in events intervening between vision and action or whether they reflect processes leading up to the generation of saccadic eye movements, is unknown. Therefore, we recorded from SNr neurons while monkeys performed our target probability task to determine whether these neurons were modulated during events preceding the initiation of a saccade.

Initially, when a single possible target appeared, SNr neurons showed a distinct pause in activity (Fig. 4, first row). The level of activity resumed during the delay period, but it did not reach levels seen during baseline. At the time the target dimmed, for a single possible target, there was not much change in the level of activity. The neuron declined more at the time the saccade was initiated. As the number of possible targets increased from one to eight, the activity profile changed. The initial decline associated with the onset of the visual stimuli was reduced with increased numbers of possible targets (Fig. 4, first column). Again the activity resumed to tonic levels but it was less than baseline. In this example neuron, the tonic level was slightly higher with eight possible targets than with one [see also 6]. At the time the target dimmed, the activity began to decline most notably when there were many stimuli present as in the eight possible target condition (Fig. 4, last row). The reduced level of activity remained until after the saccade ended at which time the activity returned to baseline (not shown).

Thus, SNr neurons, like SC neurons, are modulated by the number of possible targets available for selection. When the probability is maximal, the SNr activity associated with visual stimuli is maximal (in this case there is a maximal pause in activity). When the probability is reduced, the pause associated with visual stimuli is reduced. Whereas in the example shown here there is a modest difference in the delay period activity of neurons with different target probabilities, this is a not a general finding [see 6]. Nevertheless, the modulations of SNr activity seen with multiple possible targets indicate that these neurons, like the SC neurons, are not obligately linked to saccade generation.

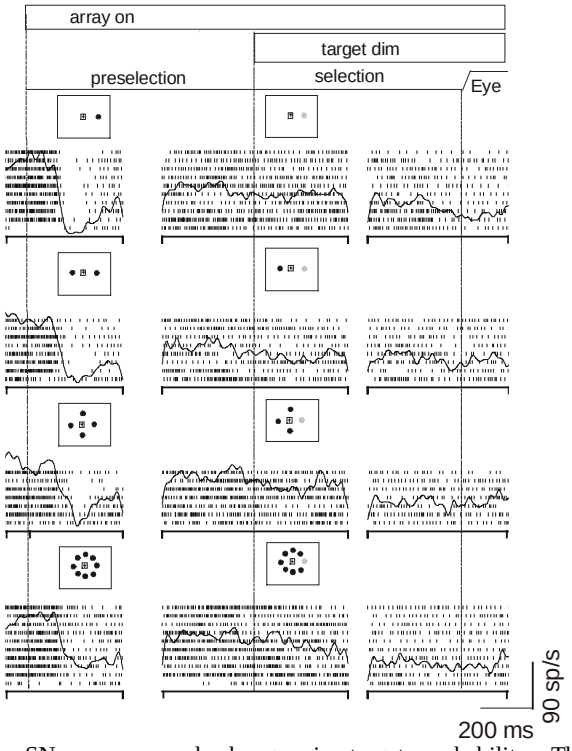

Fig. 4. SNr neuron and changes in target probability. The arrangement is identical to that in Fig. 3.

IV. DISCUSSION

We recorded from neurons in the SC and the SNr while monkeys performed a behavioral task in which either one, two four or eight possible targets appeared. After a time only one of the stimuli was indicated as the target by dimming. At this point, monkeys could select the target and prepare to make an eye movement to the location of that target. Prior to the dimming, monkeys did not know which target would be identified. With one stimulus there was 100% probability that it would dim whereas with eight possible targets, it was only 12.5% probable that that same target would dim. Consistent with the change in target probability, neurons in both of these regions were modulated. We found that SC neurons which generally show an increase in activity associated with the onset of visual stimuli and saccadic eye movements, showed high levels of activity when there was only one possible target present. As the number of possible targets increased, the activity decreased, consistent with the reduced probability. The SNr exhibited a similar pattern. SNr neurons generally show a pause in activity associated with the appearance of visual stimuli and the onset of saccadic eye movements. We found that when only one target was present, these neurons showed a maximal pause in activity and when multiple possible targets were present the pause in activity was reduced. Thus, both of these regions, tightly coupled to the generation of saccadic eye movements, are modulated by changes in the probability that a particular target will be identified for a saccadic eye movement.

During the delay period, before the saccade target was identified, SC neurons showed a dramatic modulation of activity whereas the SNr activity was modulated very little if at all [6]. This indicates that the direct and indirect descending cortical pathway, reflect multiple visual stimuli and therefore

more complicated visual scenes, differently. It also indicates that the suppressive effect of the multiple stimuli seen in the SC during this delay period does not result from an increased inhibition from the SNr. This is in contrast to proposed mechanisms of saccade initiation where the inhibition from the SNr is thought to hold off the production of a saccadic eye movement.

The initial pause in activity and reduced delay period activity seen in SNr neurons may not directly control the level of activity seen in the SC, but it may nevertheless provide a permissive effect [15]. For example, the transient pause may be enough to release the SC from tonic inhibition allowing the direct cortical inputs to the SC regulate the level of delay period activity. This hypothesis awaits further testing.

V. CONCLUSION

Both SC and SNr are intimately involved in the generation of saccadic eye movements. Indeed, the SC is considered part of the final common pathway for the generation of saccades and the SNr has long been known to tonically inhibit the SC thereby suppressing saccadic eye movements. Our experiments demonstrate that these structures are not simply coupled to the execution of saccades, rather they have activity that is modulated by demands of the task, in this case the complexity of the visual scene from which a single target would later be identified. Modulations such as these are reminiscent of those seen in cortical areas devoted to visual perception [reviewed in 16] and may reflect the similar behavioral challenge faced by both perceptual and motor systems in natural visual scenes. Indeed, the suppression of activity we measured with multiple possible targets present is also seen in visual cortical areas [17, 18]. After a target is identified, the neuronal activity changes overcoming the surround inhibition [see also 5, 6]. This is similar to that seen in visual cortical areas when attention is directed to one target among others [19, 20]. These observations may reveal a similar competitive architecture for target selection for perception and action and may provide valuable insights into our understanding of the organization of voluntary movement control.

ACKNOWLEDGMENT

I would like to thank Jennifer Pokorny for assistance during the preparation of this manuscript.

REFERENCES

[1] D. L. Sparks and R. Hartwich-Young, "The Neurobiology of Saccadic Eye Movements. The deep layers of the superior colliculus," *Rev. Oculomot. Res.*, vol. 3, pp. 213-256, 1989.

[2] A. M. Graybiel, "Organization of the nigrotectal connection: an experimental tracer study in the cat," *Brain Res.*, vol. 143, pp. 339-348, 1978.

[3] O. Hikosaka and R. H. Wurtz, "Visual and oculomotor functions of monkey substantia nigra pars reticulata. IV. Relation of substantia nigra to superior colliculus," *J. Neurophysiol.*, vol. 49, pp. 1285-1301, 1983.

[4] G. Chevalier, S. Vacher, J. M. Deniau, and M. Desban, "Disinhibition as a basic process in the expression of striatal functions. I. The striato-nigral influence on tecto-spino/tecto-diencephalic neurons," *Brain Res.*, vol. 334, pp. 215-226, 1985.

[5] M. A. Basso and R. H. Wurtz, "Modulation of neuronal activity in superior colliculus by changes in target probability," *J. Neurosci.*, vol. 18, pp. 7519-7534, 1998.

[6] M. A. Basso and R. H. Wurtz, "Inhibition, disinhibition and target selection in the primate saccadic system," *Submitted*, 2001.

[7] O. Hikosaka and R. H. Wurtz, "Visual and oculomotor functions of monkey substantia nigra pars reticulata. III. Memory-contingent visual and saccade responses," *J. Neurophysiol.*, vol. 49, pp. 1268-1284, 1983.

[8] O. Hikosaka and R. H. Wurtz, "Visual and oculomotor functions of monkey substantia nigra pars reticulata. I. Relation of visual and auditory responses to saccades," *J. Neurophysiol.*, vol. 49, pp. 1230-1253, 1983.

[9] A. Handel and P. W. Glimcher, "Quantitative Analysis of Substantia Nigra Pars Reticulata Activity During a Visually Guided Saccade Task," *J Neurophysiol*, vol. 82, pp. 3458-3475, 1999.

[10] M. A. Sommer, "Express saccades elicited during visual scan in the monkey," *Vision Res.*, vol. 34, pp. 2023-2038, 1994.

[11] J. A. Edelman and E. L. Keller, "Activity of visuomotor burst neurons in the superior colliculus accompanying express saccades," *J. Neurophysiol.*, vol. 76, pp. 908-926, 1996.

[12] D. P. Munoz and R. H. Wurtz, "Saccade-related activity in monkey superior colliculus. I. Characteristics of burst and buildup cells," *J. Neurophysiol.*, vol. 73, pp. 2313-2333, 1995.

[13] P. W. Glimcher and D. L. Sparks, "Movement selection in advance of action in the superior colliculus," *Nature*, vol. 355, pp. 542-545, 1992.

[14] O. Hikosaka and R. H. Wurtz, "The Neurobiology of Saccadic Eye Movements. The basal ganglia," *Rev. Oculomot. Res.*, vol. 3, pp. 257-284, 1989.

[15] M. A. Basso, A. S. Powers, and C. Evinger, "An explanation for reflex blink hyperexcitability in Parkinson's disease. I. Superior Colliculus," *J. Neurosci*, vol. 16, pp. 7308-7317, 1996.

[16] J. H. R. Maunsell, "The brain's visual world: Representation of visual targets in cerebral cortex," *Science*, vol. 270, pp. 764-769, 1995.

[17] B. C. Motter, "Neural correlates of feature selectivity memory and pop-out in extrastriate area V4," *J. Neurosci.*, vol. 14, pp. 2190-2199, 1994.

[18] R. Desimone and J. Duncan, "Neural mechanisms of selective visual attention," *Ann. Rev. Neurosci.*, vol. 18, pp. 183-222, 1995.

[19] J. Moran and R. Desimone, "Selective attention gates visual processing in extrastriate cortex," *Science*, vol. 229, pp. 782-784, 1985.

[20] J. H. Reynolds, L. Chelazzi, and R. Desimone, "Competitive mechanisms subserve attention in macaque areas V2 and V4," *J. Neurosci.*, vol. 19, pp. 1736-1753, 1999.